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Effect of Porous Multi-Layer Envelope System on Effective Wind Pressure of Building Ventilation

Ying-Chang Yu, Yuan-Lung Lo

Abstract**—**Building ventilation performance is an important indicator of indoor comfort. However, in addition to the geometry of the building or the proportion of the opening, the ventilation performance is also very much related to the actual wind pressure of the building. There are more and more contemporary building designs built with multi-layer exterior envelope. Due to ventilation and view observatory requirement, the porous outer layer of the building is commonly adopted and has a significant wind damping effect, causing the phenomenon of actual wind pressure loss. However, the relationship between the wind damping effect and the actual wind pressure is not linear. This effect can make the indoor ventilation of the building rationalized to reasonable range under the condition of high wind pressure, and also maintain a good amount of ventilation performance under the condition of low wind pressure. In this study, wind tunnel experiments were carried out to simulate the different wind pressures flow through the porous outer layer, and observe the actual wind pressure strength engage with the window layer to find the decreasing relationship between the damping effect of the porous shell and the wind pressure. Experiment specimen scale was designed to be 1:50 for testing real-world building conditions; the study found that the porous enclosure has protective shielding without affecting low-pressure ventilation. Current study observed the porous skin may damp more wind energy to ease the wind pressure under high-speed wind. Differential wind speed may drop the pressure into similar pressure level by using porous skin. The actual mechanism and value of this phenomenon will need further study in the future.

Keywords**—**Renault number, porous media, wind damping, wind tunnel test, building ventilation.

I. INTRODUCTION

DUE to the multi-layered or complicated surface, components have been adopted on contemporary building envelope design, the wind field on the building surface has changed significantly. This change is caused by two main effects. First, phenomenon of turbulence: when the laminar air flow gradually increases, and the building surface has a porous or heterogeneous multi-layered pattern, the air will begin to appear wavy swings. The frequency of swings and amplitude increase with the increase of flow velocity, and forms numerous micro eddies in the flow field called turbulence. The other is "dispersive resistance". This phenomenon comes from porous media, which will form aerodynamic forces that consume local kinetic energy when penetrating such media. When air travels through porous skin and reaches the target interface, the actual pressure will be lower than the initial pressure.

In the general building envelope, the external peak wind pressure will directly act on the building surface. This external wind load dominates the performance of most building envelope, including structural, protective, operable, and ventilation performances. [1]-[6] With the multi-layered design, wind loads will be dispersed on different interface layers causing attenuation, and generating the turbulence mentioned above, which will further reduce the wind pressure when it reaches the actual building surface. The higher the pressure is, the more obvious the turbulence phenomenon is. Therefore, when the ambient wind pressure increases linearly, the actual contact wind pressure on the building surface may have a non-linear change. In such case, a multi-layer building envelope with porous skin may ensure a reasonable building ventilation under the condition of high wind speed wind and resisting the damage simultaneously.

Based on the wind pressure damping phenomenon that has been found in 2017, the damping affection of the porous skin may be reduced along with the wind attack angle and the depth of the interlayer cavity. The general turbulence damping phenomenon is not only related to the air travel route, but also to the air flow velocity, which is the so-called decreasing damping phenomenon. This study conducted a series of wind tunnel test under differential wind speed to verify the impact of ambient wind speed on the damping phenomenon. It is expected that through this stage of research, it will be integrated horizontally with the field of building environmental control, and find out the effect of the porous interface on the effectiveness of indoor air ventilation.

II. HYPOTHESIS AND SCOPE OF TARGET BUILDING

A. Definition

Turbulence: Under certain conditions, the fluid can move smoothly and in an orderly manner, which called laminar flow; on the contrary, the movement of the fluid may be irregular, unsteady, and enter in a mode that seems completely mixed called Turbulence. In addition to the fluid flowing forward, air breaks into many vortices and mixes with the fluid on the side.

Renault number: It is a dimensionless quantity used to determine whether the state of the fluid is turbulent or laminar. When the Reynolds number is small, the influence of the viscous force on the flow field is greater than the inertial force. The disturbance of the flow velocity in the flow field will be attenuated by the viscous force, and the fluid flow will be stable. The effect on the flow field is greater than the viscous

Y. Y. is with the Department of Architecture, Tamkang University, No.151, Yingzhuan Rd., Tamsui, New Taipei City, Taiwan (corresponding author, phone: +886-2-26215656; fax: +886-2-26235579; e-mail: 110388@mail.tku.edu.tw).

Y. L. is with the Department of Civil Engineering, Tamkang University, No.151, Yingzhuan Rd., Tamsui, New Taipei City, Taiwan (e-mail: 142935@mail.tku.edu.tw).

force, the fluid flow is relatively unstable, and small changes in the flow rate are easy to form irregular turbulent flow field.

Natural ventilation: The process and phenomenon of air exchange and mixing inside and outside the building are the most important factor affecting indoor air quality. Natural ventilation can be divided into wind pressure ventilation and buoyancy ventilation. Wind pressure ventilation depends on the difference in wind pressure caused by the natural wind force on the building, causing air flow and indoor and outdoor air exchange.

Pressure Coefficients: The pressure coefficient is a dimensionless number describing the relative pressure across the entire flow field in fluid dynamics. As a dimensionless parameter for studying fluid flow, the pressure coefficient can be used not only to study the flow of incompressible fluids such as water, but also to study the low-speed flow of compressible gases such as air.

Porous skin: A surface consists of evenly distributed openings and have empty spaces or pores that allow foreign matter (such as water, air, and particles) to penetrate and reaches building surface. Contemporary buildings use porous façade skin to control foreign water or strong wind as rain screen or wind screen (Fig. 1).

Fig. 1 Case Study of Porous Skin [8]

B. Principle of Ventilation Performance

When the wind blows towards the building, it generates positive pressure on the windward side of the building. At the same time, air flows around the sides and back of the building, creating negative pressure at corresponding locations. Wind pressure ventilation is the use of the pressure difference between the windward and leeward sides of the building to achieve air circulation. Building ventilation is based on the air movement caused by the air pressure difference between the inside and outside of the building, which has the effect of improving indoor air quality and saving air conditioning energy consumption [7]. However, wind speed and wind pressure are deeply affected by the outer porous skin, which in turn greatly affects ventilation performance. The purpose of this study is to observe the filtering effect of porous skin on wind speed and wind pressure, and predict the change of wind pressure under different wind speeds (Figs. 2 & 3) whether there is a damping phenomenon.

C. Hypothesis

Building ventilation is affected by environmental wind speed and wind pressure. When the air is pushed by the wind speed and wind pressure and passes through the porous skin, it will produce a certain degree of filtering and damping, and then generate air turbulence. Based on the theoretical mechanism of Reynolds number, this study believes that this turbulence will form different degrees of damping under different wind speed conditions, so that more actual penetration energy of high wind speed is consumed, and then the effect of wind speed mitigation may be achieved. Moreover, the peak wind pressure coefficients may fall into similar value range due to the affection of wind turbulence.

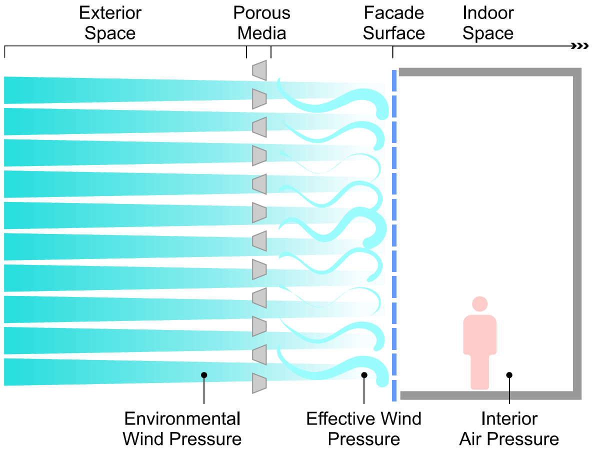

Fig. 2 Diagram of Porous Façade under High Wind Speed

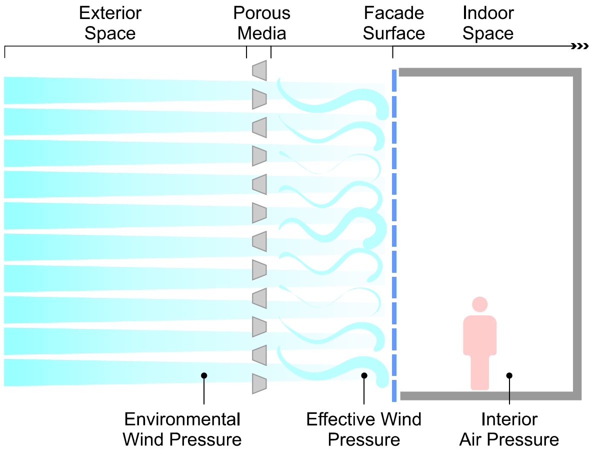

Fig. 3 Diagram of Porous Façade under Low Wind Speed

III. DESIGN OF EXPERIMENT AND IMPLEMENTATION

A wind tunnel test was conducted to verify the effect of pressure reduction behind porous windscreen

A. Design of Testing Model

The testing model was designed into a dual-layered square boxes made by 0.3 mm acrylic sheet to represent a building with porous windscreen.

The inner box consists with pressure sensor array and PVC transducer to collect wind pressure data. The outer shell contains pores to simulate the porous windscreen conditions, and could be replaced for various scale or shape of windscreen (see Fig. 4).

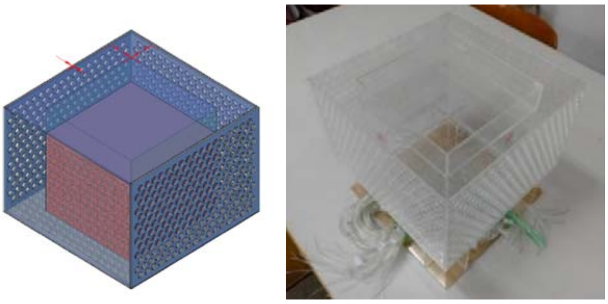

Fig. 4 Model of Sensor Array with Porous Windscreen

B. Scale of Testing Model

The testing specimen is a 1:50 scale model to replicate a building with porous windscreen. According to the theory of local wind speed and building scale, the environment wind speed shall be 40 m/sec. The testing wind high-speed is 10 m/sec. So the testing speed scale is 1/4, and time scale is 1/12.5. In such case, a 10-minute actual wind movement would equal to 48 seconds wind tunnel test. A grill panel was installed to generate air turbulence in order to replicate the actual environmental wind pattern. The estimated Reynolds number is 5.3, 8.0, 10.7, and 13.3 × 10^4, which correspond to the selected mean wind speeds, 4, 6, 8, and 10 m/sec at the model height with the building width B of 0.2 m. These estimated Reynolds numbers are in the commonly simulated range in the wind tunnel tests for buildings. The inner building model is installed with pressure taps over its four faces as shown in Fig. 5.

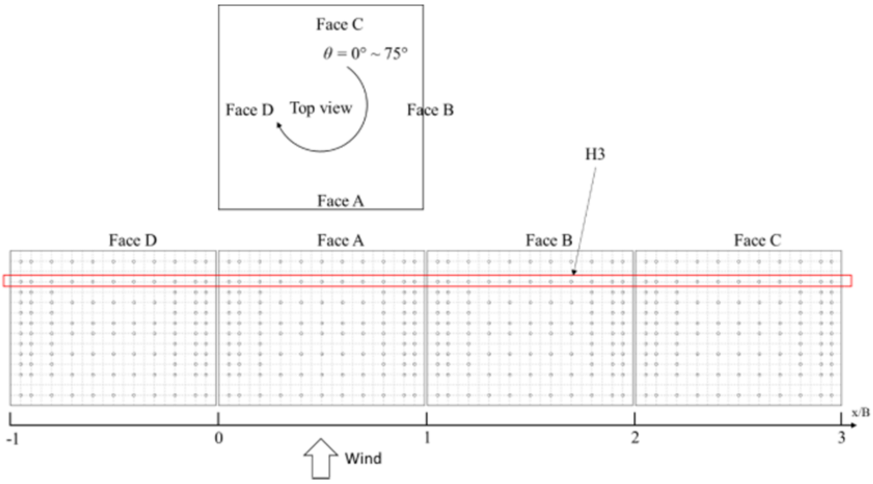

Fig. 5 The plain view of four faces of the inner building

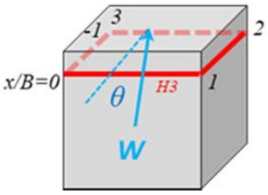

Fig. 6 Pressure Orientation Diagram

The model is fixed at the turntable center and rotates to 0°, 15°, 30°, 45°, 60°, and 75° wind directions for pressure measurements. Two model configurations are chosen for the test – the bare building model and the building model covered with the porous façade skin of 50% porosity percentage. Pressure taps along elevation H3 are selected for subsequent examinations. Pressures are simultaneously recorded via a multi-channel scanning system (SCANIVALE) and then corrected for tubing effects by an inverse Fast Fourier Transform technique with the transfer and phase functions of the 1.3-mm-inner-diameter vinyl tube. Pressure coefficients are then calculated by normalizing measured pressures with the mean velocity pressure at the building model height (see Fig. 6).

IV. TESTING RESULTS AND FINDINGS

A. Surface Pressure Coefficient Pattern

The data collected from various testing model alone with the effect of the Reynolds number are similar to the results in Fig. 7. The mean pressure coefficients are relatively stable alone with Reynolds number. With the affection of the porous facade skin, significant differences are only seen at the edges x /B = 0, 1 for θ = 0°, 2 and x/B = 0, 2 for θ = 45°; although the overall distribution of the pressure coefficient of the test model decreased slightly due to the porous skin and the depth of the cavity.

Low wind speed velocity (Fig. 7) and high wind speed velocity (Fig. 8) share similar mean wind pressure coefficient pattern under various attack angles. For ventilation performance purpose, this research focuses on the region from x/B = 0 to x/B = 1 and wind attack angle θ = 0° to simulate peak pressure condition.

B. Comparison of Surface Pressure behind Porous Skin

Readings of surface wind pressure on bare building in scale were recorded as shown on Table I, and surface wind pressure behind porous wind screen was recorded as shown on Table II.

Corresponding readings of surface pressure on bare surface and behind porous screen are obviously decreased matching to the hypothesis mentioned in Section II *C*. When air passes through porous screen at higher wind speed, the wind pressure is observed to drop much more than the wind pressure at lower wind speeds.

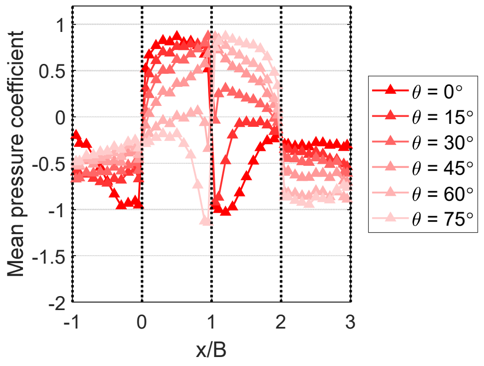

Fig. 7 Mean pressure coefficients of 5.3 × 10^4 along H3 without porous façade skins

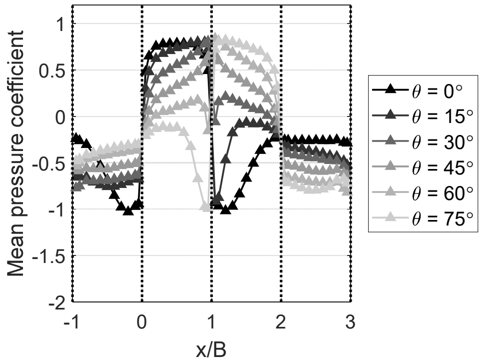

Fig. 8 Mean pressure coefficients of 13.3 × 10^4 along H3 without porous façade skins

TABLE I
SURFACE WIND PRESSURE WITHOUT POROUS SKIN (PA)

x/B	4 m/sec	6 m/sec	8 m/sec	10 m/sec
0.05	16.25451	34.67041	58.19649	88.34185
0.10	17.81323	38.32399	65.47603	99.92757
0.20	19.79645	40.78352	69.84906	106.4167
0.30	19.73	41.42142	71.98066	109.6074
0.40	19.45541	40.54815	71.85355	109.2773
0.50	19.81591	41.56107	73.67687	110.175
0.60	19.81213	41.94588	72.20313	110.12
0.70	19.68378	41.84941	72.3632	110.0966
0.80	19.70803	41.51619	70.71791	108.6019
0.90	18.5314	38.82689	66.13397	102.5313
0.95	16.42592	34.62778	59.22566	91.47219

Each wind speed has its own wind damping ratio as shown in Fig. 9. Higher surface pressure was observed on middle area and it may be caused by the transfer pressure from both sides of testing surface. Surface wind pressure was also observed to be dropped more significantly on both sides of testing surface than middle area. The possible reason is that the testing porous screen was designed to be an open system, and air could flow freely from side cavity matching to small scale buildings.

TABLE II
SURFACE WIND PRESSURE BEHIND POROUS SKIN (PA)

x/B	4 m/sec	6 m/sec	8 m/sec	10 m/sec
0.05	11.47352	23.63356	44.28055	64.38313
0.10	12.39095	28.77975	48.916	74.4295
0.20	15.00655	34.65474	59.41418	92.18008
0.30	16.56723	37.69319	65.37959	99.56379
0.40	16.71746	38.25886	67.09426	102.0562
0.50	17.68142	39.33721	69.35333	103.3691
0.60	17.25153	39.48955	69.95986	103.0951
0.70	17.027	37.87425	66.79423	99.98899
0.80	15.45672	34.86331	62.36104	92.53744
0.90	13.0651	29.7594	53.09913	78.95354
0.95	11.18301	25.95125	46.24851	67.07085

C. Comparison of Peak Wind Pressure Coefficients

Pressure coefficients are then calculated by normalizing measured pressures with the mean velocity pressure at the building model height. The converted peak wind pressure coefficients are listed as Table II for bare build and Table IV for building behind porous wind-screen.

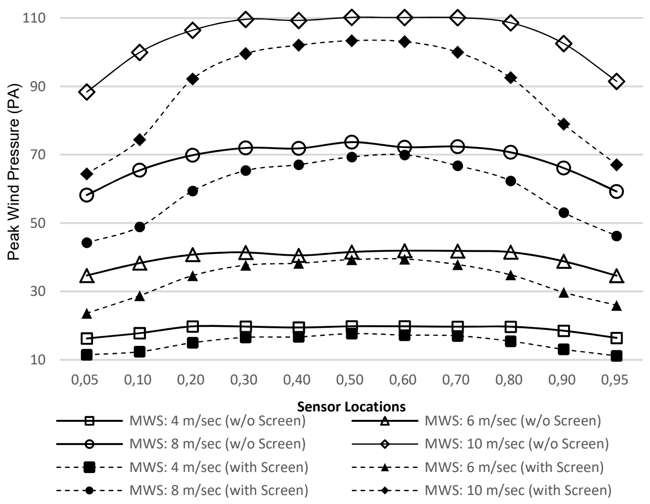

Fig. 9 Surface Wind Pressure along H3 between x/B 0 and 1

TABLE III
PEAK PRESSURE COEFFICIENTS WITHOUT POROUS SKIN

x/B	Re = 5.3E4	Re = 8.0E4	Re = 10.7E4	Re = 13.3E4
0.05	1.6654	1.5788	1.4907	1.4482
0.10	1.8251	1.7452	1.6772	1.6382
0.20	2.0283	1.8572	1.7892	1.7445
0.30	2.0215	1.8862	1.8438	1.7968
0.40	1.9934	1.8465	1.8405	1.7914
0.50	2.0303	1.8926	1.8872	1.8061
0.60	2.0299	1.9101	1.8495	1.8052
0.70	2.0168	1.9057	1.8536	1.8049
0.80	2.0193	1.8905	1.8114	1.7804
0.90	1.8987	1.7681	1.6940	1.6808
0.95	1.6830	1.5769	1.5171	1.4995

TABLE IV
PEAK PRESSURE COEFFICIENTS BEHIND POROUS SKIN

x/B	Re = 5.3E4	Re = 8.0E4	Re = 10.7E4	Re = 13.3E4
0.05	1.1756	1.0762	1.1342	1.0555
0.10	1.2696	1.3106	1.2530	1.2202
0.20	1.5376	1.5781	1.5219	1.5111
0.30	1.6975	1.7164	1.6747	1.6322
0.40	1.7129	1.7422	1.7186	1.6731
0.50	1.8116	1.7913	1.7765	1.6946
0.60	1.7676	1.7982	1.7920	1.6901
0.70	1.7446	1.7247	1.7109	1.6392
0.80	1.5837	1.5876	1.5974	1.5170
0.90	1.3386	1.3552	1.3601	1.2943
0.95	1.1458	1.1818	1.1846	1.0995

The wind pressure coefficients for bare building under different wind speed are recorded and drew in solid line in Fig. 10. The corresponding wind pressure coefficients for building behind porous wind-screen are recorded and drewn in dash line in Fig. 10.

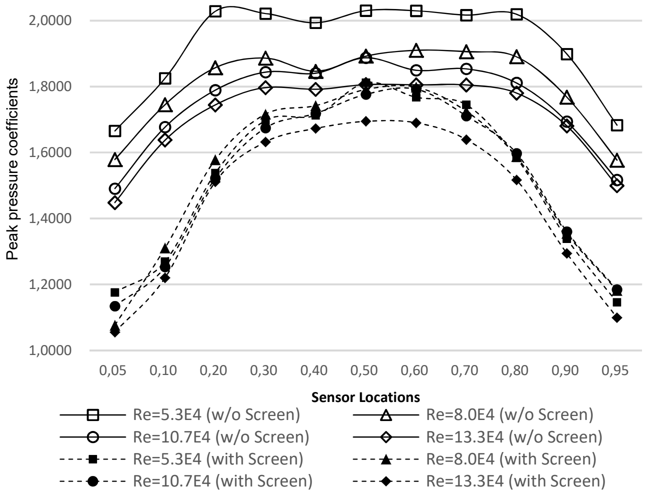

Fig. 10 Peak Pressure Coefficients along H3 between x/B 0 and 1

The recorded values on dash lines for building behind porous skin are relatively stable and concentrated in closer range than the solid lines for bare building. The figure of wind pressure coefficients shows the wind damping mechanism is affective to normalize the pressure, and it may be useful for rationalizing wind pressure for ventilation.

V. CONCLUSION

Ventilation in contemporary building, especially high-rise building, is facing to extreme wind condition, and requiring high speed wind to be rationalized for comfortable ventilation environment. Current study observed that the porous skin may damp more wind energy to ease the wind pressure under high-speed wind. Differential wind speed may drop the pressure into similar pressure level by using porous skin. The actual mechanism and value of this phenomenon will need further study in the future.

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